Optimized Traffic Engineering Techniques for Efficient QoS Implementation in Software Defined Wireless Networks

Synopsis of the Thesis to be submitted in Partial Fulfillment
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Doctor of Philosophy

by

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Abstract

Wireless networks have always been the focus of research; however involve the challenges such as low packet delivery rate, inefficient network management, lack of global monitoring, etc. Software Defined Networking (SDN) can be helpful to counter these challenges, and improve the performance of the existing wireless networks. Wireless networking technology supporting SDN evolves as a new networking domain called Software Defined Wireless Network (SDWN), having numerous applications including Internet of Things (IoT). Considering its inherent complex structure, plethora of network components, dynamics, and heterogeneity, Quality of Service (QoS) has been a critical concern. This issue can be addressed by using Traffic Engineering (TE) to optimize different network functions. The optimization leads to the enhancement of Flow management, Fault tolerance, Topology update, and Traffic analysis. Therefore, the resultant multi-fold benefits motivate to explore optimized TE-based solutions for efficient QoS implementation in SDWNs.

In this thesis work, different optimized TE-based solutions have been demonstrated to improve the overall QoS in targeted SDWNs. Solution 1 presents an optimized link utilization based approach for TE in SDWN. The method uses the multi-commodity based optimized link utilization approach to improve the network flow-cost by 10%. To improve the QoS-based overall flow management, Solution 2 discusses a QoS aware optimized TE approach for efficient flow management in IoT network called QuOTE. In addition to the multi-commodity based optimized link utilization, the approach uses network flow optimization to minimize the network congestion and improve the packet loss ratio. The experimental results highlight an overall average efficiency of *9.15%, 21.83%, 17.59%*, and *11.05%* against the major QoS metrics, namely Packet Delivery Ratio (PDR), Packet Loss Ratio (PLR), Average Delay (AD), and Average Jitter (AJ), respectively. Further, Solution 3 named as Opt- ACM is presented to address the admission control issue along with the network flow based load balancing. It highlights the concept of load-balanced traffic assignment and optimized link utilization to improve network performance. Opt-ACM exhibits an average improvement of *9.47%*, *12.32%*, *26.77%* and *33.10%* against PDR, PLR, AD, and AJ, respectively. Moreover, the energy and trust issues have been considered as important performance factors in SDWNs. Hence, Solution 4 is designed to offer the energy and trust issues based solution named Energy Optimized Multi-Constraints based Sustainable Routing (EOMCSR) model for SDWN. Furthermore, network policy update plays a crucial role in preventing link failures in the networks. In this direction, an Optimal Policy Update Mechanism (Opti-PUM) has been designed for link failure prevention in IoT network as Solution 5. This solution uses various network statistics (*Link_Flow, Link_RSSI, Link_Bandwidth, Link_Error_Rate, etc*.) to improve the network performance. Finally, efficient traffic analysis can also be used to improve the network performance. Thus, Solution 6 and 7 have been implemented to offer the binary and multi-class classification approach for the varying time granular traffic in IoT networks, respectively. The solutions analyze the varying time granular traffic at different levels, namely Coarse, Medium, and Fine granularity, and offer a minimum accuracy of 98%.

The proposed solutions offer multi-fold benefits to optimize the performance of different underlying SDWN architectures. The validity of all solutions is verified and tested against some state-of-the-art solutions. The performance is assessed against standard QoS performance metrics. As conclusion, the work helps to improvise the level of QoS in the SDWNs.

Keywords: *Software Defined Networking (SDN), Software Defined Wireless Networks (SDWNs), Traffic Engineering (TE), Quality of Service (QoS), Internet of Things (IoT).*

1. Introduction

Wireless networks offer numerous benefits in terms of increased efficiency, Access and availability, Flexibility, Cost savings, etc., and have been under active exploration from research point of view. However, there are multiple challenges raising concerns such as low packet delivery rate, inefficient network management, lack of global monitoring, real-time programming, etc. These challenges can be countered in an effective way using Software Defined Networking (SDN). SDN separates the data plane from the control plane in a network [1]. SDN can help to improve the management and configuration of wireless networks. The unique features of SDN allow global network monitoring, network programming, agile network management, effective fault tolerance, etc. The merge of SDN with wireless networks gives rise to a new technological domain called Software defined wireless networks (SDWNs).

Similar to wireless networks, SDWNs also have wide applications. One of the prominent applications is the Internet of Things (IoT). IoT envisions connecting all low power devices across the world. However, there have been numerous practical constraints, including compatibility, interoperability, authentication, connectivity, etc. Thus, it becomes a really challenging task to manage the Quality of Service (QoS) in SDWN considering its inherently complex structure, plethora of network components, dynamic and heterogeneous constraints, etc. [2]. Traffic-Engineering (TE) can be used in such environmental conditions to improve network performance. TE is a well-known domain of engineering practices used to handle efficient QoS implementation in networks. The optimized form of these practices helps to improve flow management, fault tolerance, policy updates, etc. The resultant multi-fold benefits encourage the use of optimized TE in SDWNs. This motivates us to propose some Optimized TE-based solutions for efficient QoS implementation in SDWNs.

2. State of the Art[1]:

Some of the existing works have attempted to apply the TE techniques in SDWNs to counter the respective networking challenges. Few of them are mentioned here to discuss the importance of TE solutions in SDWNs. A lightweight flow management approach is discussed in [3] offering flow-table management in SDWSN whenever a fault occurs in the data plane. The concept of link load information has been discussed in [4], which is fetched from the network in real time. Based on the bandwidth requirement of the data flow, the improved load balanced routing is applied in the SDWSN. The work detailed in [5] proposes a fault tolerant framework for a centralized controller in SDWSN. The approach is targeted for small and medium sized networks. The work explored in [6] highlights the significance of designing an energy-efficient sensor scheduling and management strategy with guaranteed quality-of-sensing for all tasks. The work investigate sensor activation, task mapping, and the sensing scheduling in detail. The topology discovery and QoS management issues have been elaborated in [9] with a focus on efficient network configuration. The work discusses the efficiency of SDWMN architecture with a controller discovering network topology and monitoring QoS parameters of WMN. The work detailed in [8] highlights the node mobility based traffic balancing issue. It discusses a mechanism to predict the node mobility and link failure probability, which helps to achieves the optimal traffic balancing while minimizing the control plane overhead. The importance of traffic classification and the role of ML in this process have been discussed in detail in [9]. The work offers the insights on ML techniques based effective traffic identification and classification. Similarly, the work detailed in [10] performs a controller-based

[1] R. Kumar, U. Venkanna, and V. Tiwari, "Optimized Traffic Engineering in Software Defined Wireless Network based IoT (SDWN-IoT): State-of-the-Art, Research Opportunities and Challenges", *IEEE Communications Surveys and Tutorials.* **[Communicated]**

network traffic analysis for choosing a better metric for switch hand-offs. The approach claims to improve the network performance with an added functionality of network traffic based analysis.

3. Motivation and Objectives:

TE offers numerous network performance benefits; nonetheless, there are different associated challenges in its effective implementation. As improper flow management may lead to the network throughput degradation, flow management techniques need to take care of effective load balancing, efficient flow table handling, etc. [3], [4]. On the other hand, network lifetime may get reduced in absence of network fault tolerance [5], [6]. Thus, fault tolerant approaches are supposed to optimize the energy consumption, improve the network lifetime, etc. In addition to above, the out-dated topological updates may also impact the effective network state building, which may futher lead to the unsuitable network policy formation [7], [8]. Hence, topology update mechanisms are meant to maintain the real-time network state, effective network-wide policies, etc. Finally, the network data management may not be effective in case of inaccurate traffic classification process [9], [10]. In this way, some traffic analysis methods are required to monitor the network traffic pattern changes, perform accurate traffic analysis, etc. However, it's important to manage different research issues of each of these categories to counter all above mentioned challenges and to improve the overall network performance. Therefore, the presented dissertation focuses on the possibilities of optimized TE in SDWNs, and to propose some related solutions incorporating the above-mentioned research issues. The role of optimized TE in wireless networks has been illustrated in Fig. 1.

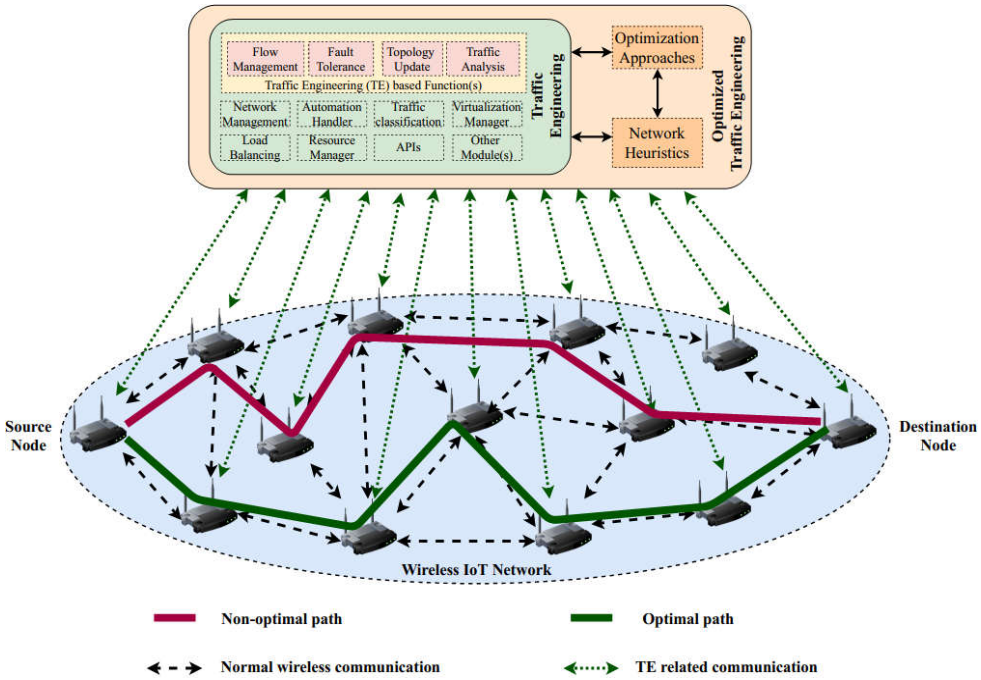


Fig. 1: Optimized TE in wireless environment

By getting motivated from the above mentioned points, the common objectives of the Thesis are:

- To study the different TE-based SDWN technologies and architectures related to traffic measurement (e.g., network parameters measurement, traffic analysis, and prediction, etc.) and traffic management (e.g., traffic load balancing, QoS-guaranteed scheduling, energy-saving scheduling, traffic management, etc.)

- To propose some Network Flow Optimization based Solutions for optimized TE in the SDWN focusing on the optimized network resource utilization (e.g., link bandwidth, flow rate, load balancing, admission control, etc.) in the network to improve the overall network performance.
- To offer some Fault Tolerance Optimization based Solutions to improve the network health condition and prolong the network lifetime.
- To provide some Topology Update Optimization based Solutions to maintain the best possible network state leading to the effective network policies formulation.
- To propose some Traffic Classification Optimization based Solutions for efficient TE implementation in SDWN, resulting in effective network traffic behaviour understanding and improved traffic management.

4. Description of Research works

4.1 Proposed Solution 1: Optimized Link Utilization Based Approach for Traffic Engineering in SDWSN[2]

In Wireless Sensor Network (WSN), resource optimization is one of the challenging issues. It improves the network performance. This can be achieved with the help of new networking technology called Software Defined Networking (SDN). The concept of SDN is to decouple the control plane from the forwarding plane of a network to improve the performance of the networking applications. Traffic Engineering (TE) is a domain of network applications that manage the network traffic and tries to optimize the network resources. SDN offers multiple features to support TE applications. SDN combined with WSN forms a new networking domain called Software Defined WSN (SDWSN). Since WSN has resource-constrained nodes, resource optimization is a need in WSN. This work proposes an optimized link utilization based approach for TE in SDWSN. The proposed approach discusses a traffic optimization algorithm called Optimized Link Allocation based TE (OLA-TE).

Algorithm 1 OLA-TE (G,T,W)

```
Input: G, T, W
Output: MNU
current_weights = Neighbour_search (G, W);
current_utilizations = All_pair_short_path (G,
current_weights);
best_utilizations = current_utilizations;
current_weights = W;
best_weights = W;
for each iteration time, do
    current_weights = Neighbour_search (G, W);
    current_utilizations = All_pair_short_path (G,
    current_weights));
    if current_utilizations < best_utilizations
        best_utilizations = current_utilizations;
        best_weights = current_weights;
MNU = best_utilizations;
```

Resource optimization in SDWSN is an important issue as it helps to improve the QoS in the network. The controller node needs the dynamic updates from the sensor nodes to have real-time network optimization. This dynamic update needs a mechanism to modify the weights of the graph in a continuous way accordingly. As the dynamic weights update is an NP-complete problem, the heuristic algorithms are used as a solution. By considering the constraints of the WSN, an algorithm

[2] R. Kumar, U. Venkanna, and V. Tiwari, "Optimized Link Utilization Based Approach for Traffic E-ngineering in SDWSN", *International Conference on Advanced Networks and Telecommunications Systems (ANTS), IEEE*, pp. 1-6, 2019. DOI: 10.1109/ANTS47819.2019.9118068. **(Best Paper award)**

named Optimized Link Allocation based TE (OLA-TE) is proposed. It is detailed in the form of Algorithm 1. It is a global search heuristic algorithm that runs at the controller node.

OLA-TE is implemented at the controller node and helps to improve the overall network utilization. The SDN sensor nodes find the optimized path for traffic routing with the help of the controller node. The relevant results of MNU in the form of objective function value, and operational nodes and energy consumption, are shown in Fig. 2 and 3, respectively.

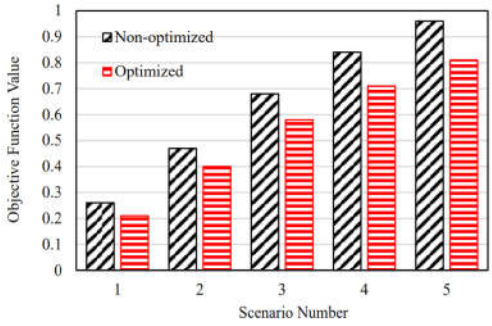


Fig. 2: Comparison of MNU for optimized and non-optimized cases

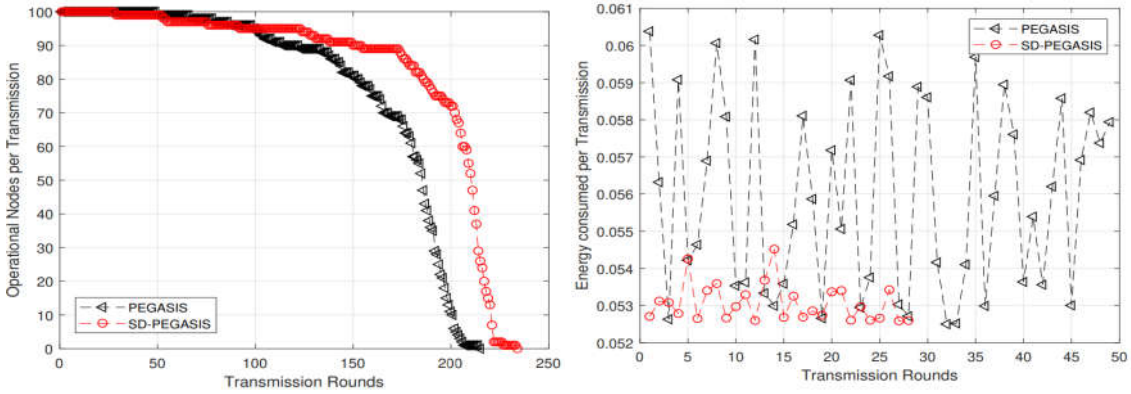


Fig. 3: Operational nodes and energy consumption per transmission round graphs

The proposed approach is compared with the traditional WSN approach. IBM CPLEX Optimization Studio and MATLAB are used for validation purposes. The CPLEX results assure a network flow-cost optimization of about 10%. The results of MATLAB show that despite having extra control traffic on the network, the network performance gets improved over the period of time.

4.2 Proposed Solution 2: QuOTE: A Quality of Service aware Optimized Traffic Engineering Approach for Efficient Flow Management in SDWS-IoT Networks[3]

Quality of Service (QoS) is a serious concern in future generation networks such as Software Defined Wireless Sensor based Internet of Things (SDWS-IoT). Optimized Traffic Engineering (TE) approaches can be used to improve QoS in agile network management. Flow management is one of the popular TE techniques. This work proposes a QoS aware optimized TE approach for efficient flow management in the SDWS-IoT network, called QuOTE. It collects the network-wide link QoS

[3] R. Kumar, U. Venkanna, and V. Tiwari, "QuOTE: A Quality of Service aware Optimized Traffic Engineering Approach for Efficient Flow Management in SDWS-IoT Networks", *IEEE Communications letters*. **[*Revision under process]**

statistics and computes the optimized path with respect to different network QoS constraints. The architecture of the proposed SDWS-IoT network is shown in Fig. 4. It consists of the controller node, IoT sink node, and multiple IoT sensor motes. The sensor motes sense the environment and forward the data packets to the sink mote in a multi-hop fashion.

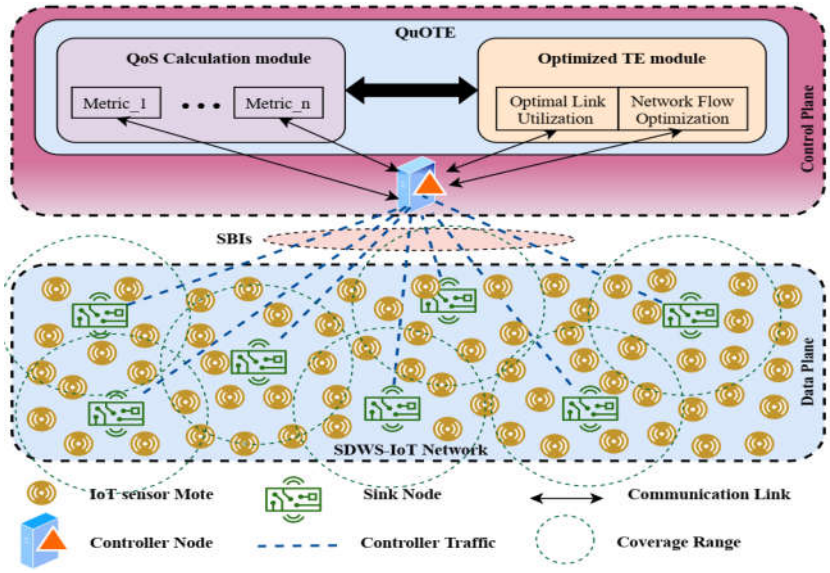


Fig. 4: Conceptual architecture of the proposed solution (QuOTE)

The sink nodes' behaviour and network topology is maintained by the controller node using the standard South Bound Interfaces (SBIs). The controller calculates the network-wide optimal link utilization and optimizes the network flow periodically, using the Optimized TE module. Similarly, the network-wide QoS is maintained using the QoS calculation module, which uses different network performance metrics such as energy, delay, jitter, etc.

The comparison is performed against some well-known QoS metrics, namely Packet Delivery Ratio (*PDR*), Packet Loss Ratio (*PLR*), Average Delay (*AD*), and Average Jitter (*AJ*). PDR and PLR are directly related to the effective bandwidth utilization of the network. Similarly, AD and AJ depend on the processing speed of the forwarding devices and clock period variations, respectively. Some of the network performance parameters and QoS metrics based results have been shown in Fig. 5 and 6.

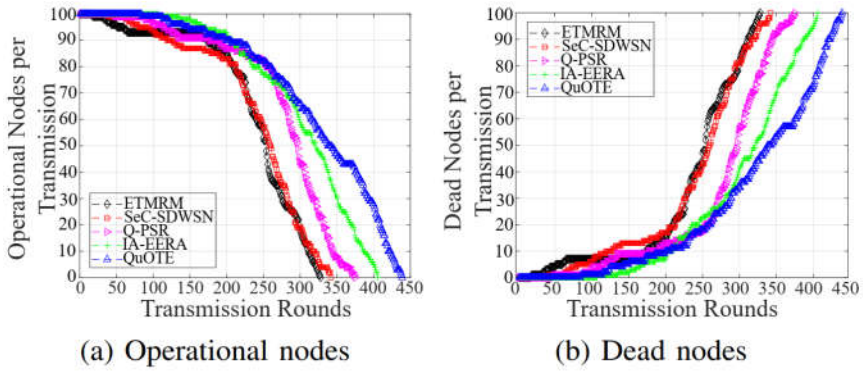


Fig. 5: Various network performance parameters for varying Transmission rounds

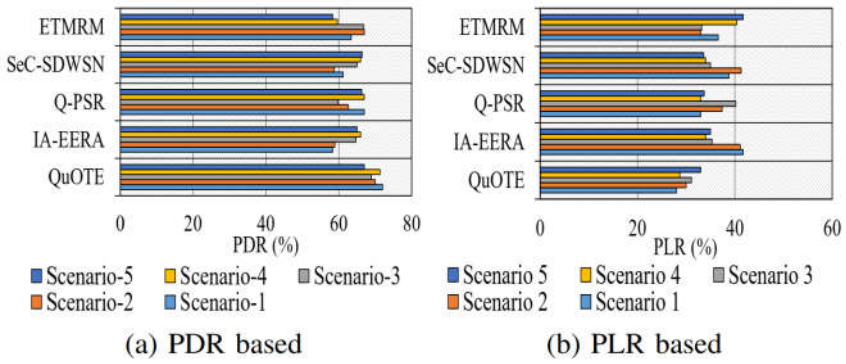


Fig. 6: QoS metrics based comparison of different approaches

The proposed solution is implemented using CPLEX Optimization solver, MATLAB, and Python APIs. The results are compared with the state-of-the-art approaches w.r.t. some well-known QoS metrics. QuOTE offers the substantial efficiency of 9.15%, 21.83%, 17.59%, and 11.05% over other approaches for PDR, PLR, AD, and AJ metrics, respectively.

4.3 Proposed Solution 3: Opt-ACM: An Optimized Load Balancing based Admission Control Mechanism for Software Defined Hybrid Wireless based IoT (SDHW-IoT) Network[4]

The wide network applications of Internet of Things (IoT) urge the integration of different wireless networking technologies. However, the associated challenges such as security, installation issues, coverage, and transmission speed, impulse for a prominent solution like Software Defined Networking (SDN) to alleviate these challenges. The growing number of IoT users produces a massive volume of traffic, causing heavy network load conditions, resulting in a state of network congestion. This state of network congestion may cause severe network performance issues such as frequent packet drops, longer delays, low throughput, etc. Thus, a promising solution is needed to reduce and/or prevent this state of congestion. This work presents an Optimized load balancing based Admission Control Mechanism (Opt-ACM) for effective network flow management resulting in a reduced network congestion state. In addition to this, the paper highlights the challenges of the existing solutions and discusses a Software Defined Hybrid Wireless based IoT (SDHW-IoT) network architecture, consisting of Software Defined Wireless Sensor Network (SDWSN) and Software Defined Wireless Mesh Network (SDWMN).

The proposed architecture of the SDHW-IoT network is shown in Figure 7. It consists of two network domains, namely, SD-WSN and SDWMN. Each of these domains has a centralized controller i.e., Sensor Controller (SC) and Access Point Controller (APC). The controllers are responsible for managing different types of networks i.e., sensor network and mesh network.SC collects the periodic updates from the distributed sensor and controls the flow admission process in the network using the Admission control module. APC handles the mesh nodes and balances the network load in overload situations using the Load balancing module. Additionally, multiple controllers increase the fault tolerance of the network. Some common modules are listed in the architecture to maintain the simplicity of the architecture and highlight the similarity between both controllers. SC and APC collectively formulate the control plane of the SDHW-IoT network and get synchronized with each other periodically using the synchronization link.

[4] R. Kumar, U. Venkanna, and V. Tiwari, "Opt-ACM: An Optimized load balancing based Admission Control Mechanism for Software Defined Hybrid Wireless based IoT (SDHW-IoT) network", *Computer Networks*, vol. 188, pp. 107888, 2021. DOI: 10.1016/j.comnet.2021.107888

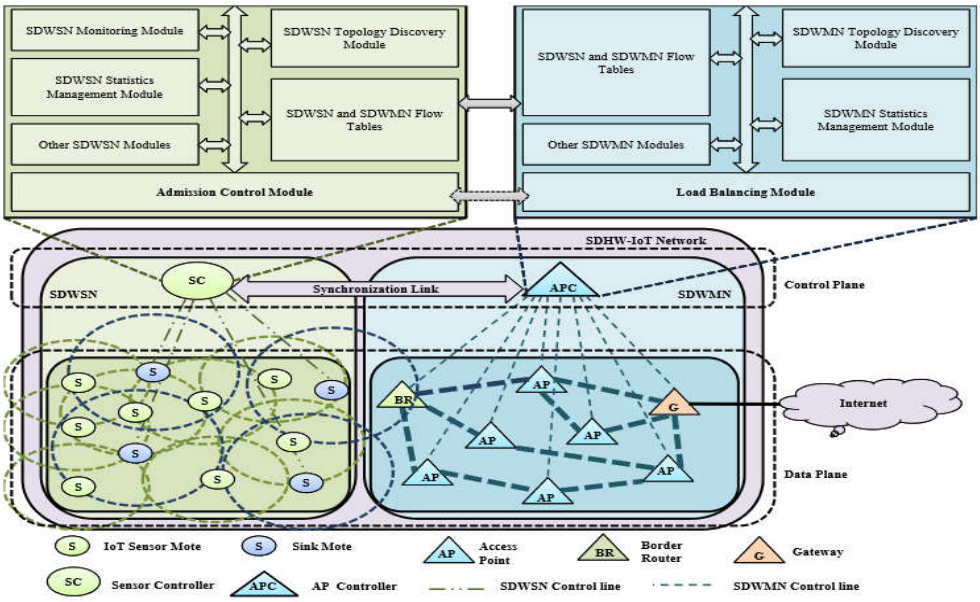


Fig. 7: Proposed Architecture

To validate the efficiency of Opt-ACM, a Mixed-Integer Linear Programming (MILP) based optimization problem is formulated and tested using a well-known mathematical optimization solver called Gurobi. Additionally, Opt-ACM is also emulated in Mininet-Wifi with a varying number of network scenarios against some traditional and state-of-the-art approaches. This work used some prominent network performance metrics to analyze the performance of the proposed mechanism. These metrics offer in-depth analysis of Opt-ACM against other approaches. The analysis is performed under different network scenarios with a varying number of IoT sensor motes, sink motes, APs, etc. The achieved results have been shown in the form of Fig. 8.

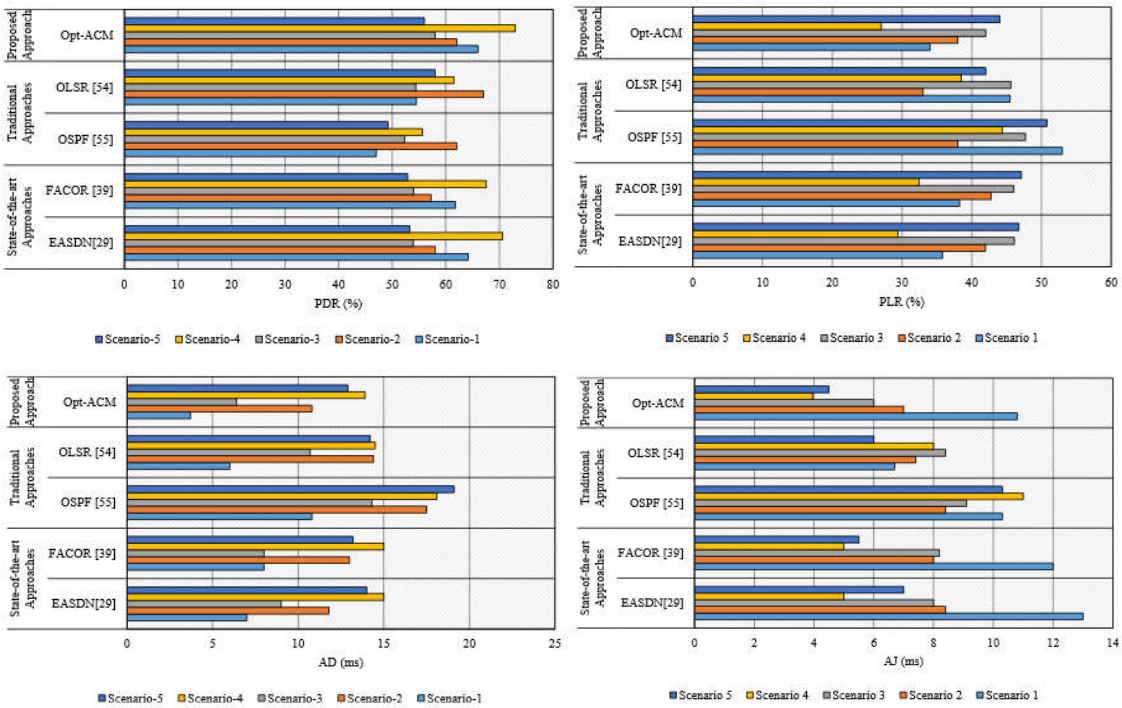


Fig. 8: QoS metrics (PDR, PLR, AD, and AJ) metrics based comparison of different approaches

Opt-ACM achieves an overall efficiency of 9.47% and 12.32 % over other approaches for PDR and PLR, respectively. Similarly, average improved efficiency of 26.77% and 33.10% are achieved with respect to the AD and AJ metrics, respectively.

4.4 Proposed Solution 4: EOMCSR: An Energy Optimized Multi-Constraints based Sustainable Routing Model for SDWSN[5]

Wireless Sensor Networks (WSN) is an important part of future networks because of their unique role in diverse situations. Improving the network lifetime is very important in WSN due to the limited network resources. As the sensor nodes are usually deployed in a random fashion in remote areas, energy optimization and fault tolerance become major concerns. Energy optimized and fault-tolerant WSN offers improved routing performance. The routing performance of a WSN could further be improved with the help of Software Defined Networking (SDN). The integration of SDN with WSN introduces the Software Defined Wireless Sensor Networks (SDWSNs). SDWSN exploits the benefits of SDN to make WSN energy-efficient and robust. A similar energy-efficient approach is proposed in this work. This work proposes an SDWSN based Energy Optimized Multi-Constraints based Sustainable Routing (EOMCSR) approach. The proposed EOMCSR formulates a Mixed-Integer Linear Programming (MILP) problem to optimize the energy consumption in the network, which further results in a sustainable network. The proposed architecture is shown in Fig. 9.

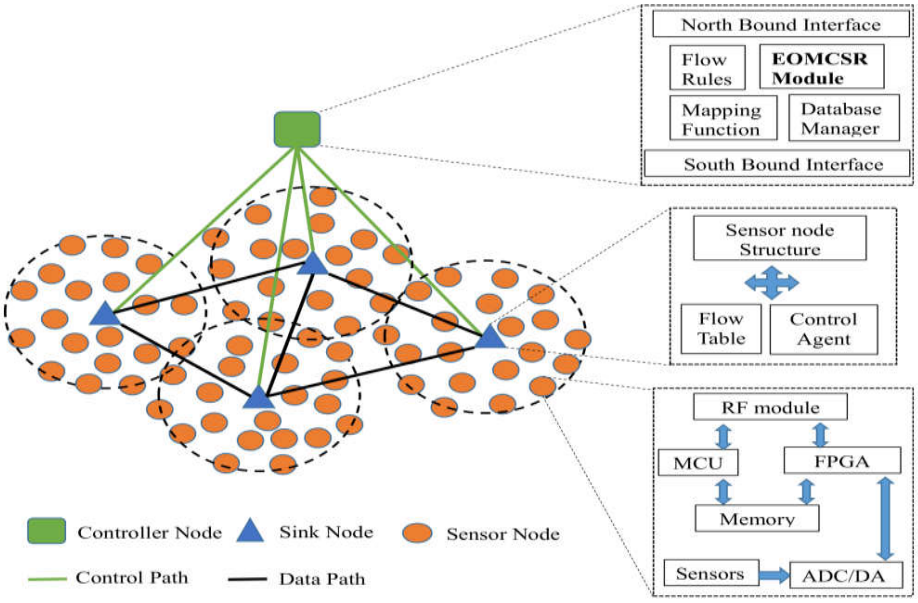
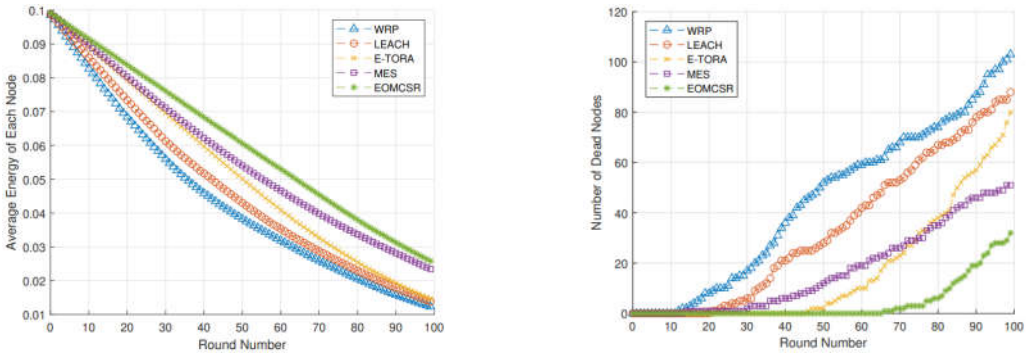


Fig. 9: Proposed SDWSN architecture

The proposed approach executes inside the controller node. The approach has two working phases. In the first phase, the controller executes the standard WSN routing algorithm LEACH. The controller determines the possible routing paths. In the second phase, the approach optimizes the routing process by choosing the minimum weight nodes. The minimum weight paths are calculated based on energy levels and other constraints. Finally, the forwarding rules of nodes are updated.

[5] R. Kumar, U. Venkanna, and V. Tiwari, "EOMCSR: An Energy Optimized Multi-Constraints based Sustainable Routing Model for SDWSN", *IEEE Transactions on Network and Service Management (TNSM)*. **[*Revision under process]**

The MILP problem is solved with GUROBI commercial solver and python APIs. The algorithm is proposed for energy-optimized routing in SDWSN, which is implemented using MATLAB. The results are compared with other SDWSN based and traditional WSN approaches with respect to average energy per node consumption and the number of dead nodes for the different number of rounds. The presented results prove the efficiency of the proposed approach. The simulation environment is used to verify the feasibility of the proposed SDWSN approach over other protocols. The optimization constraints are added to the simulation environment to testify the performance results. The proposed SDWSN approach is compared with an SDWSN protocol named MultiEnergy Space (MES) and some traditional WSN protocols named Wireless Routing Protocol (WRP), Energy-aware Temporarily Ordered Routing Algorithm (E-TORA), and Low energy adaptive clustering hierarchy (LEACH). The comparison results are shown in the form of Fig. 10 and 11.



a) Average energy graph b) Number of dead nodes

Fig. 10: Average energy and Number of dead nodes based comparison for 100 rounds

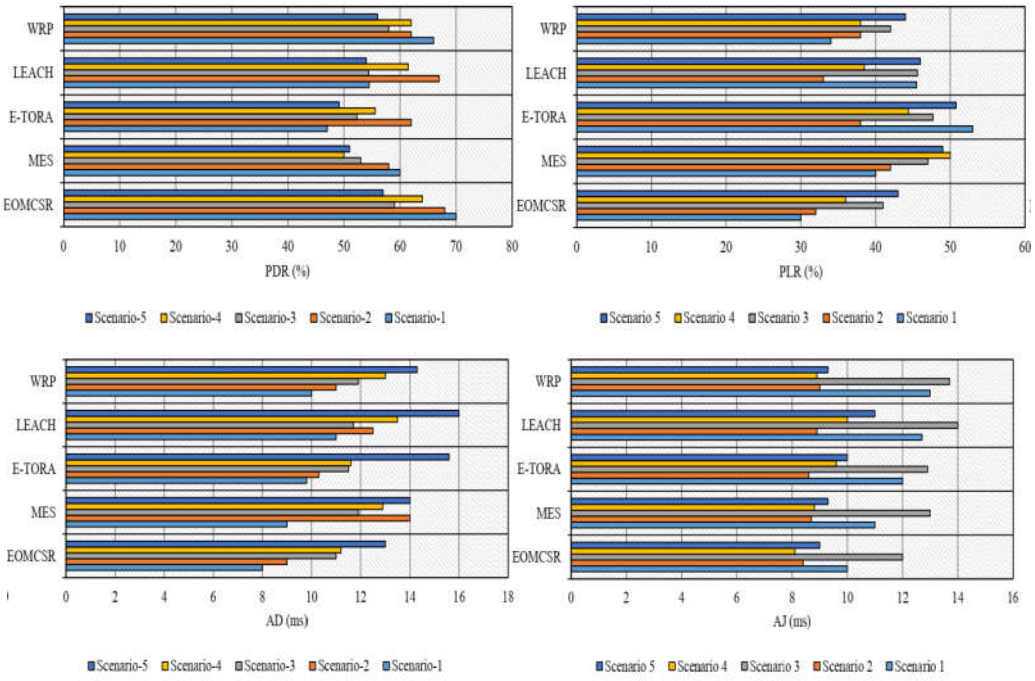


Fig. 11: QoS metrics (PDR, PLR, AD, and AJ) based comparison of different approaches

The simulation results show that the proposed EOMCSR achieves an efficiency of around 36% and 60% for the number of dead nodes in comparison to the existing SDWSN approach (MES) and traditional approach (E-TORA), respectively, after 100 rounds. Similarly, an efficiency of around 8%

and 48% is achieved for average energy per node in comparison to the existing SDWSN approach (MES) and traditional approach (E-TORA), respectively, after 100 rounds.

4.5 Proposed Solution 5: Opti-PUM: An Optimal Policy Update Mechanism for Link Failure Prevention in Mobile SDWM-IoT Networks[6]

Due to the limited resources and several implementation challenges, frequent link failure is a serious concern in mobile wireless mesh-based Internet of Things (WM-IoT) networks. The unique features of software defined networking (SDN), such as global visibility, network programmability, etc., help to improve the fault tolerance and network management in IoT networks. The integration of SDN and WM-IoT networks leads to a new domain, called software defined WM-IoT (SDWM-IoT) networks. This article discusses the problems caused by the frequent link failures in mobile SDWM-IoT networks. Most of the existing works focus on link failure prevention by precomputing backup paths, link monitoring-based failure detection, etc. However, limited efforts have been devoted to adaptive multi-constrained link failure prevention. This article proposes a proactive optimal policy update mechanism named Opti-PUM, as shown in Fig. 12.

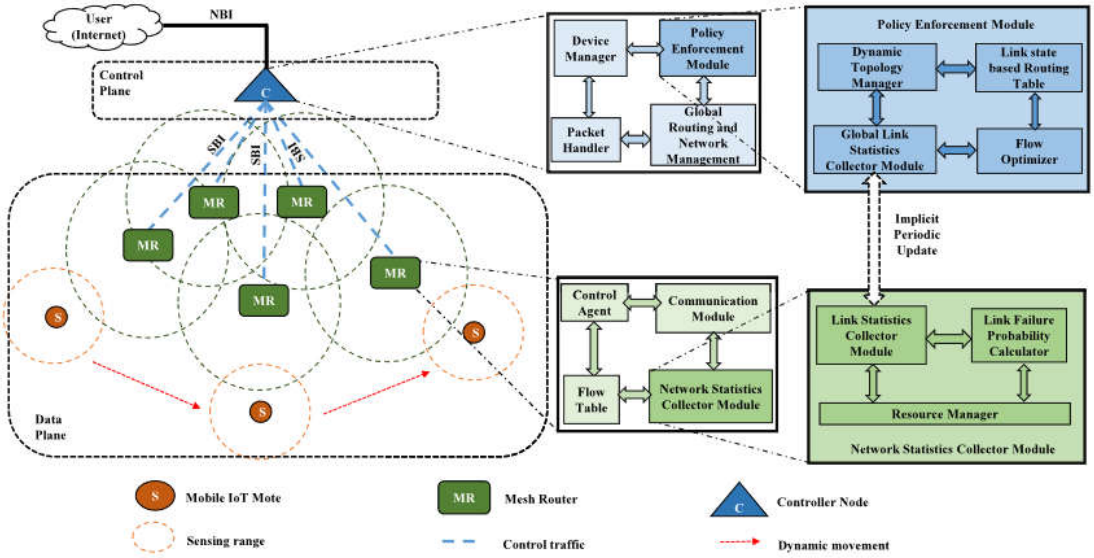


Fig. 12: Proposed Architecture

The sensor motes in the data plane collect the data and forward to the respective MR using the proposed network statistics collector module. All the collected data statistics are forwarded to the controller using the control agent. The controller receives the data statistics of all sensor motes and updates the global routing table. The flow entries of the global routing tables are optimized by the flow optimizer, and the proposed policy enforcement module formulates the new policy based on the optimized flow entries to improve the overall network traffic flow. This process gets repeated periodically in the control plane, and the procedure gets terminated after processing all the traffic flows.

The approach is formulated in a promising algebraic modeling language (AMPL) and is solved using a well-known algebraic solver (CPLEX). Opti-PUM is tested under various network scenarios. Additionally, the proposed approach is also implemented in Mininet-WiFi, and the obtained results

[6] R. Kumar, U. Venkanna, and V. Tiwari, "Opti-PUM: An Optimal Policy Update Mechanism for Link Failure Prevention in Mobile SDWM-IoT Networks", *IEEE Systems Journal*, 2020. DOI: 10.1109/JSYST.2020.3009325

are compared with some well-known existing algorithms. The simulation is performed for both cases, i.e., With and Without-OptiPUM. The With-OptiPUM case amalgamates the proposed Opti-PUM with the traditional WMN protocols. Each case evaluates different WMN protocols with respect to five different networking scenarios, with the varying number of mobile IoT sensor motes, MRs, and gateways. Some of the achieved results have been shown in Fig. 13.

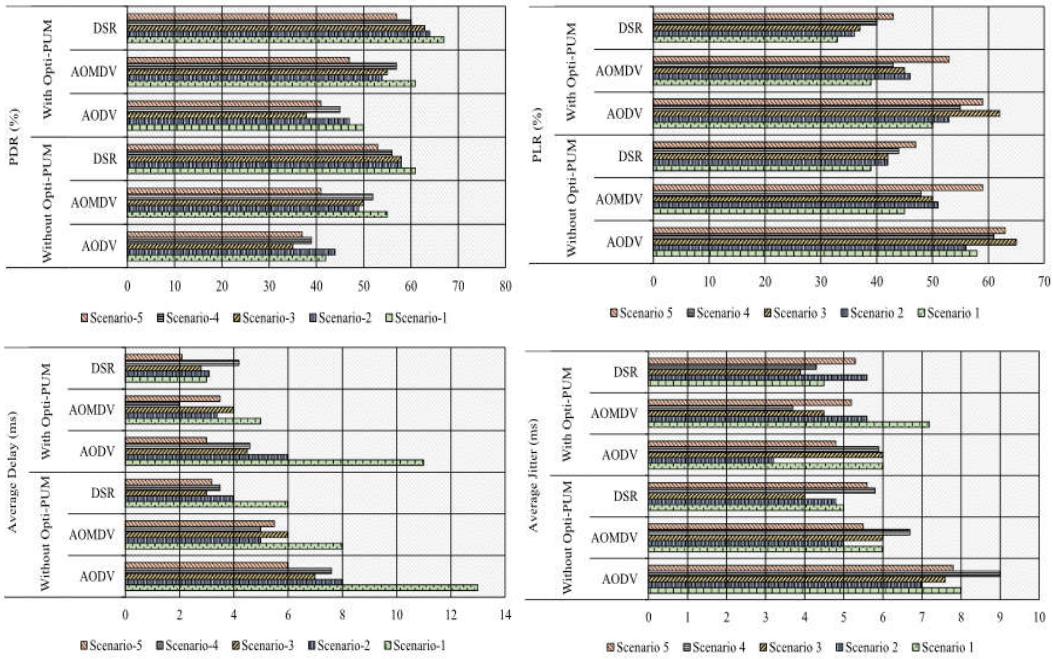


Fig. 13: QoS metrics (PDR, PLR, AD, and AJ) based comparison of different approaches

The comparison shows that Opti-PUM helps to achieve the PDR and PLR improvement of 12.18% and 11.68%, respectively. Similarly, an AD and AJ improvement of 35.93% and 31.72% have also been achieved.

4.6 Proposed Solution 6: A Binary Classification Approach for Time Granular Traffic in SDWMN based IoT Networks[7]

Wireless Mesh Networks (WMNs) constitute a major part of modern wireless Internet of Things (IoT) networks. The long-distance routing performance in wireless IoT networks can be improved by utilizing the unique features of Software Defined Networking (SDN). Employing the SDN technology with WMN results in Software Defined WMN (SDWMN). The architectural independence of SDN allows having more wireless users and devices in SDWMN networks. This results in a mammoth amount of traffic generation. Various traffic-engineering techniques are employed to manage such massive traffic. Traffic Classification (TC) is one such technique. TC proves to be beneficial in numerous applications such as firewall building, intrusion detection, status report generation, etc. Time granularity-based TC helps to achieve these objectives, which results in improved network management. This work performs the binary classification on time-granularity-based IoT network traffic by employing different Machine Learning (ML) techniques. Some well-

[7] R. Kumar, U. Venkanna, and V. Tiwari, "A Binary Classification Approach for Time Granular Traffic in SDWMN based IoT Networks", *12th International Conference on COMmunication Systems & NETworkS (COMSNETS), IEEE*, pp. 531-534, 2020. DOI: 10.1109/COMSNETS48256.2020.9027336

known ML techniques such as Decision Tree (DT), Support Vector Machine (SVM) and K-Nearest Neighbour (KNN) are used for classification purposes. The proposed architecture is shown in Fig. 14.

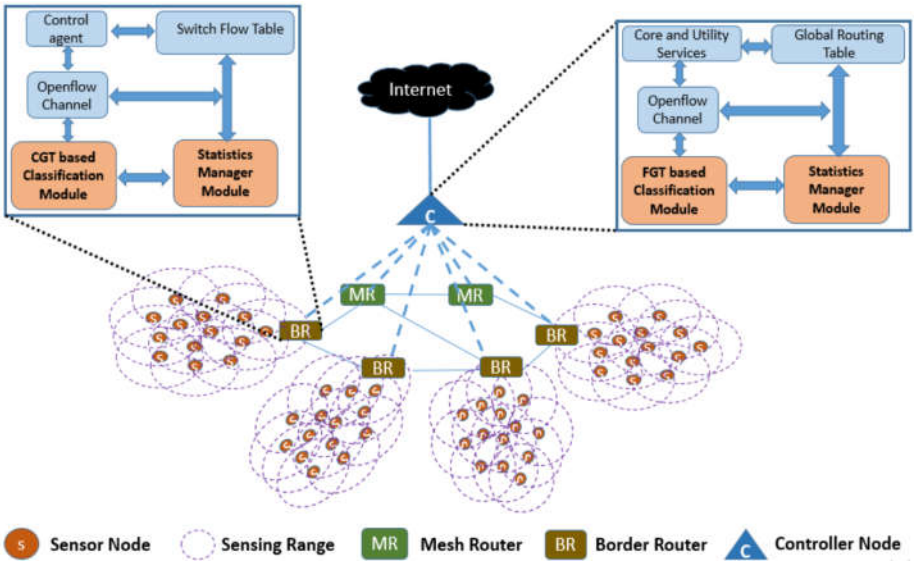


Fig. 14: Proposed flow classification architecture for varied granularity datasets

An 802.15.4 MAC layer performance dataset is used. The dataset provides the measurements collected from the wilab2 testbed facility in Ghent and is provided on GitHub. The dataset consists of multiple time-based multi-granular data subsets. The subsets have different OTPs. The dataset is divided into FGT and CGT subsets. The features and the ML classifiers used for the classification are detailed in Tables 1 and 2, respectively.

Table 1: Features used for classification

S. No.	Feature Name	Feature Definition
1	*NumOfReceived*	Number of received frames
2	*PRR*	Packet Reception Rate
3	*PacketLoss*	Number of erroneous frames
4	*PLR*	Packet Loss Rate
5	*Throughput*	Aggregated throughput
6	*IPI*	Inter-Packet-Interval
7	*Density*	Number of active nodes

Table 2: ML classifiers used for classification

S. No.	Acronym	Classifier Name
1	*F_DT*	Fine DT
2	*M_DT*	Medium DT
3	*C_DT*	Coarse DT
4	*L_SVM*	Linear SVM
5	*Q_SVM*	Quadratic SVM
6	*C_SVM*	Cubic SVM
7	*FG_SVM*	Fine Gaussian SVM
8	*MG_SVM*	Medium Gaussian SVM
9	*CG_SVM*	Coarse Gaussian SVM
10	*F_KNN*	Fine KNN
11	*M_KNN*	Medium KNN
12	*Coa_KNN*	Coarse KNN
13	*Cos_KNN*	Cosine KNN
14	*Cu_KNN*	Cubic KNN
15	*W_KNN*	Weighted KNN

DT variant is a simple and widely used classification technique with high prediction speed, less memory usage and ease of interpretability. F_DT has high model flexibility. This allows making very fine distinctions among output classes. M_DT allows medium number of leaves for output class distinction. C_DT model's flexibility is the lowest, and only a few leaves are used for coarse distinction among classes. SVM variants are popular prediction models to solve a variety of problems such as classification, regression, etc.

C_SVM consumes average memory but shows fast prediction speed for binary classification. FG_SVM has high flexibility, which helps to classify the output classes at a fine level. MG_SVM

shows a medium level of flexibility. CG_SV_M exhibits prediction speed with medium memory consumption. KNN variants are also widely used for different purposes such as classification and regression. F_KNN distinguishes the output classes at fine levels. M_KNN shows an average speed of output class prediction. Coa_KNN exhibits average prediction speed and coarse level of distinction among output classes. Cos_KNN distinguishes the output classes using a cosine distance metric. Cu_KNN uses a cubic distance metric to predict output classes but exhibits low prediction speed. W_KNN uses a weight-based distance metric to predict the output class. The accuracies of different ML classifiers for FGT and CGT datasets are shown in Fig. 15. The Maximum and minimum accuracies achieved by different classifiers for FGT and CGT datasets are also depicted in Fig. 16 and 17, respectively.

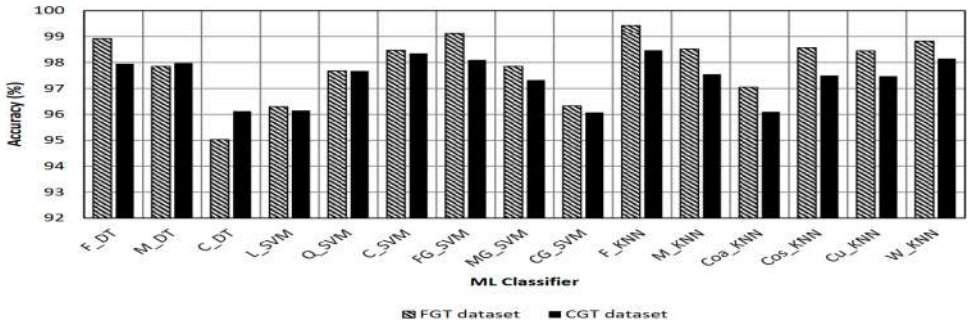


Fig. 15: Average accuracy of ML classifiers for FGT and CGT datasets

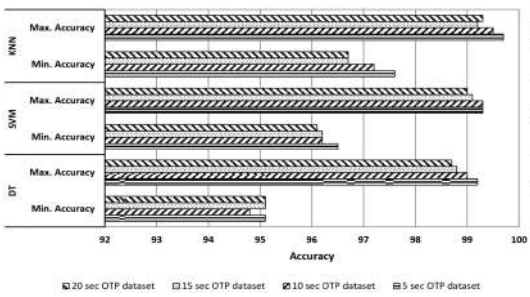


Fig. 16: Max and Min accuracy of ML classifiers for FGT

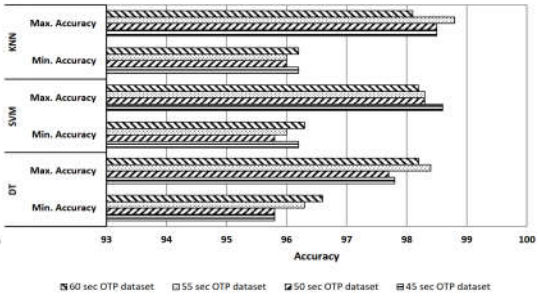


Fig. 17: Max and Min accuracy of ML classifiers for CGT

All of the ML algorithms offer a reliable accuracy of more than 90%. Out of all techniques, FineKNN produces the best accuracy for most of the traffic classes with a rate of more than 98%. All classification accuracies are verified with a cross-validation technique of 10-fold to prevent the chances of over-fitting. This verified accuracy assists in choosing the suitable classifier in future network applications to assure improved network performance.

4.7 Proposed Solution 7: A Time Granular Analysis of Software Defined Wireless Mesh Based IoT (SDWM-IoT) Network Traffic Using Supervised Learning[8]

The ceaseless increase in the number of wireless Internet of Things (IoT) devices has resulted in the need for different traffic engineering techniques to manage the massive network traffic. Wireless Mesh Networks (WMNs) are the important constituent part of wireless IoT networks and are helpful to route the IoT networks' traffic over long distances. The WMN devices are powerful in

[8] R. Kumar, U. Venkanna, and V. Tiwari, "A Time Granular Traffic based Study of the SDWMN based IoT Networks using Machine Learning based Binary Classification Approach", *Wireless Personal Communications*, vol. 116, pp. 2083-2109, 2021. DOI: 10.1007/s11277-020-07781-6

comparison to the IoT sensor devices and are suitable to run the traffic engineering algorithms. To further improve the performance of the WMNs, Software Defined Networking can be used. Its unique features like global visibility, agility, etc., guarantee optimal network management. As granularity plays an important role in data analysis and none of the existing works has discussed a time granularity-based network data analysis, this work tries to offer a time granular analysis of Software Defined Wireless Mesh based IoT (SDWM-IoT) network's traffic using supervised learning approaches. A time granular analysis helps to explore the functional traits of the data at the Coarse, Medium, and Fine granularity levels. This assists in divulging and understanding the hidden characteristics and behaviour of the SDWM-IoT network's data based on varying time granularity, respectively. Some well-known supervised learning algorithms are used to offer an in-depth analysis of the traffic and to draw relevant conclusions.

The paper proposes a traffic classification architecture for a varied granular dataset for IoT services-based networks. Fig. 18 shows the conceptual view of the proposed SDWM-IoT network's architecture. The IoT sensors send the sensed values to the BR in a single or multi-hop fashion. The sensor nodes have a CGT-based classification module, and the BRs have an MGT-based classification module. These modules help to classify the very less frequent and less frequent observation traffic at the data plane level, respectively, which further helps to improve TC time by updating the IoT nodes' and MRs' flow tables accordingly.

Among DT variants, F_DT again shows the best accuracy of 97.8%, 97.7%, and 98.2% for 45, 50, and 60 s OTP-based subsets, respectively. M_DT produces an accuracy of 97.7% and 98.4% for 50 and 55 s OTP-based subsets. C_SVM produces the best accuracy for all coarse granular OTP-based traffic subsets as an SVM classifier. FG_SVM also achieves the best accuracy of 98.3% for 55 s OTP-based subset. F_KNN shows the best accuracy for all coarse granular OTP-based traffic subsets as a KNN classifier. Fig. 19 shows the classification accuracies for different datasets. Similar to FGT class, F_DT shows the best accuracy of 98.8%, 98.7%, and 98.3% for 25, 30, and 40 s OTP-based subsets, respectively. M_DT produces an accuracy of 98.3% for 35 s OTP-based data subset.

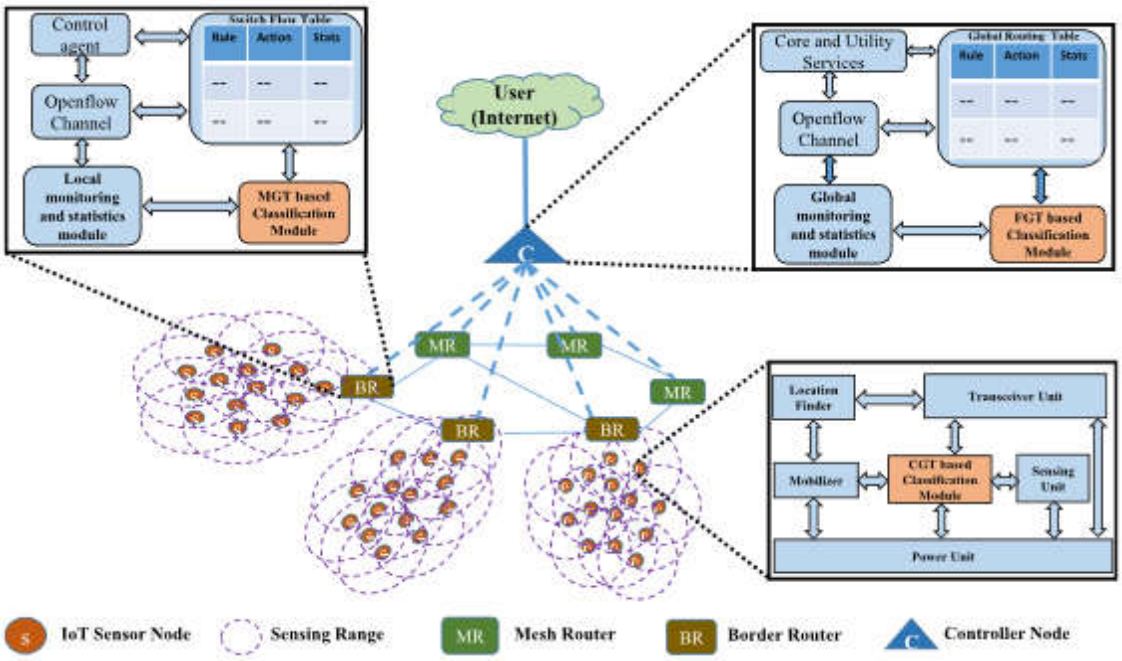


Fig. 18: Proposed architecture

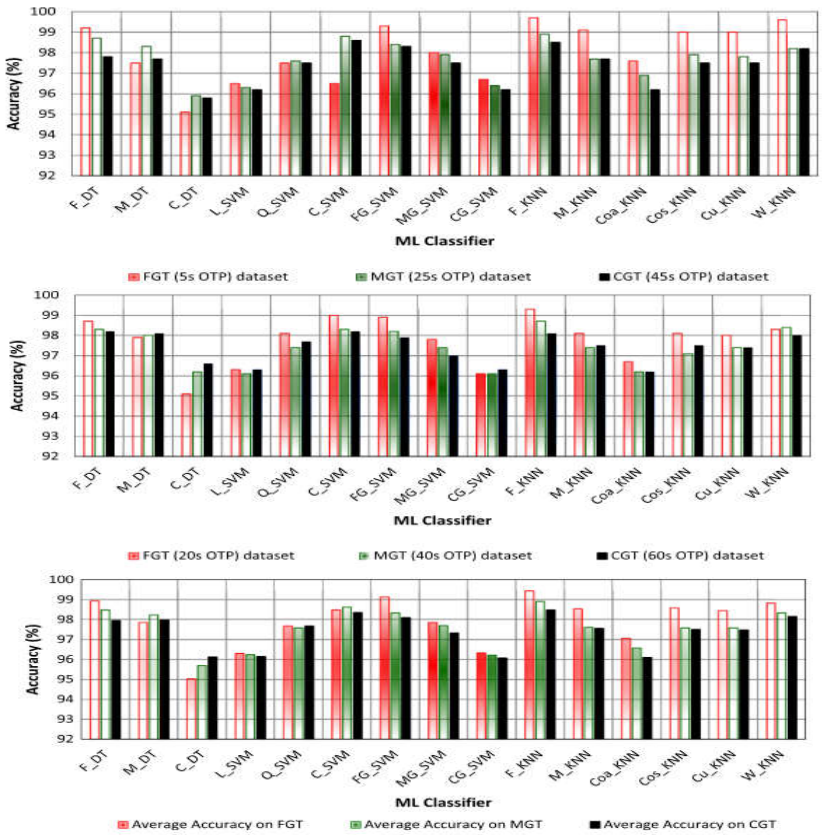


Fig. 19: Lower range, Higher range, and Average accuracy results for varying granularity datasets

Different variants of Decision Tree, Support Vector Machine, and K-Nearest Neighbour (KNN) are used to analyze the traffic and achieve a reliable accuracy rate of more than 90%. Among all the variants, fine-KNN produces the best accuracy for most of the traffic classes with a rate of more than 98%. In addition to this, a tenfold cross-validation technique is also used to prevent the chances of over-fitting.

5. Major Contributions of the Thesis:

The important contributions of the thesis are outlined below.

I. Different TE-based SDWN technologies and architectures related to traffic measurement (e.g., network parameters measurement, traffic analysis, and prediction, etc.) and traffic management (e.g., traffic load balancing, QoS-guaranteed scheduling, energy-saving scheduling, traffic management, etc.) have been explored and discussed.

II. Some Network Flow Optimization based Solutions have been proposed for optimized TE in the SDWNs focusing on the optimized network resource utilization

III. A Fault Tolerance Optimization based Solution is discussed to improve the network health condition and prolong the network lifetime.

IV. A Topology Update Optimization based Solution is presented to optimize the the policy update mechanism in the network leading to the overall network performance improvement.

V. Some Traffic Classification Optimization based Solutions have been offered for efficient TE implementation in SDWNs, resulting in effective network traffic behaviour understanding.

6. Comparative Analysis of Proposed Solutions:

The proposed solutions are developed to overcome the drawbacks of the existing solutions in terms of different QoS metrics such as Network flow cost effectiveness, Energy efficiency, PDR, PLR, AD, and AJ. Solution 1 offers flow-cost optimization of about 10% in comparison to PEGASIS [11]. Similarly, Solution 2 outperforms some of the state-of-the-art approaches, namely ETMRM [12], SeC-SDWSN [13], Q-PSR [14], and IAEERA [15], w.r.t. Number of operational nodes, Average energy consumption per node, PDR, PLR, etc. Solution 3 also excels against some traditional (OLSR [16] and OSPF [17]) and state-of-the-art (FACOR [18] and EASDN [19]) approaches against some well-known QoS metrics PDR, PLR, AD, and AJ. Solution 4 achieves the performance improvement for Average energy of each node, Number of dead nodes, etc., against MES [20], WRP [21], E-TORA [22], and LEACH [23]. Likewise, Solution 5 achieves the functional efficiency using AODV, AOMDV, and DSR protocols against PDR, PLR, AD, and AJ metrics. Finally, Solution 6 and 7 achieve the classification accuracies of more than 98 % for different variants of DT, SVM, and KNN.

7. Conclusion and Future Scope:

The role and impact of SDWNs in the IoT environment are well known. Wireless networks help to improve the possibilities of IoT networking in remote, dense, and practically unsuitable geo-locations. SDN assists in enhancing the performance of wireless networks; nevertheless, the role of TE can not be ignored. This work explores the multiple TE-based practices, opportunities, and challenges in the effective implementation of SDWN-IoT networks. The two main categories of SDWN-IoT, namely, SDWSN-IoT and SDWMN-IoT, are investigated to uncover their role and responsibilities in the actual realization of IoT vision.

The future work of this work aims to explore the remaining SDWN categories w.r.t. the state-of-the-art IoT implementation possibilities. Additionally, the implementation and role of SDWNs in the realization of other prominent technologies such as CPS, IIoT, etc., can also be investigated.

8. Organization of the Thesis:

The thesis will comprise of following six chapters:

I. **Chapter-1**: Introduces the basic introduction and state-of-the-art architectures in SDWNs. Additionally, the motivation behind the work, research objectives, thesis organization, and major contributions have also been detailed.
II. **Chapter-2:** Describes different Network Flow Optimization based Solutions. The work covers different underlying architectures, problem definitions, proposed solutions, and results-based analysis.
III. **Chapter-3:** Presents a detailed Fault Tolerance Optimization based Solution. The work also highlights the major contributions, system model, problem formulation, and results-based performance analysis.
IV. **Chapter-4:** Illustrates the Topology Update Optimization based Solutions. The work offers novel contributions, proposed system model and optimization approach, experimental results, and the relevant analysis.

V. **Chapter-5:** Discusses the different Traffic Classification Optimization based Solutions. The work covers the underlying architectures, traffic classification approaches, performance evaluation, and results-based analysis.

VI. **Chapter-6:** Contains the conclusion and future work. General summary, limitations of the presented works, and the related future works have been highlighted.

9. Publications from the Thesis

Journal(s):

I. R. Kumar, U. Venkanna, and V. Tiwari, "Opti-PUM: An Optimal Policy Update Mechanism for Link Failure Prevention in Mobile SDWM-IoT Networks", *IEEE Systems Journal*, 2020. DOI: 10.1109/JSYST.2020.3009325

II. R. Kumar, U. Venkanna, and V. Tiwari, "A Time Granular Traffic based Study of the SDWMN based IoT Networks using Machine Learning based Binary Classification Approach", *Wireless Personal Communications*, vol. 116, pp. 2083-2109, 2021. DOI: 10.1007/s11277-020-07781-6

III. R. Kumar, U. Venkanna, and V. Tiwari, "Opt-ACM: An Optimized load balancing based Admission Control Mechanism for Software Defined Hybrid Wireless based IoT (SDHW-IoT) network", *Computer Networks*, vol. 188, pp. 107888, 2021. DOI: 10.1016/j.comnet.2021.107888

IV. R. Kumar, U. Venkanna, and V. Tiwari, "EOMCSR: An Energy Optimized Multi-Constraints based Sustainable Routing Model for SDWSN", *IEEE Transactions on Network and Service Management (TNSM).* **[*Revision under process]**

V. R. Kumar, U. Venkanna, and V. Tiwari, "QuOTE: A Quality of Service aware Optimized Traffic Engineering Approach for Efficient Flow Management in SDWS-IoT Networks", *IEEE Communications letters*. **[*Revision under process]**

VI. R. Kumar, U. Venkanna, and V. Tiwari, "Optimized Traffic Engineering in Software Defined Wireless Network based IoT (SDWN-IoT): State-of-the-Art, Research Opportunities and Challenges", *IEEE Communications Surveys and Tutorials*. [Communicated]

Conference(s):

I. R. Kumar, U. Venkanna, and V. Tiwari, "Optimized Link Utilization Based Approach for Traffic E-ngineering in SDWSN", *International Conference on Advanced Networks and Telecommunications Systems (ANTS), IEEE*, pp. 1-6, 2019. DOI: 10.1109/ANTS47819.2019.9118068 **(Best Paper award)**

II. R. Kumar, U. Venkanna, and V. Tiwari, "A Binary Classification Approach for Time Granular Traffic in SDWMN based IoT Networks", *12th International Conference on COMmunication Systems & NETworkS (COMSNETS), IEEE*, pp. 531-534, 2020. DOI: 10.1109/COMSNETS48256.2020.9027336

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